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# Domestic fridge-freezer load aggregation to support Ancillary Services

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## ABSTRACT

Grid operators and electricity retailers in Ireland manage peak demand, power system balancing and grid congestion by offering relevant incentives to consumers to reduce or shift their load. The need for active consumers in the home using smart appliances has never been greater, due to increased variable renewable generation and grid constraints. In this paper an aggregated model of a single compressor fridge-freezer population is developed. A price control strategy is examined to quantify and value demand response savings during a representative winter and summer week for Ireland in 2020. The results show an average reduction in fridge-freezer operating cost of 8.2% during winter and significantly lower during summer in Ireland. A peak reduction of at least 68% of the average winter refrigeration load is achieved consistently during the week analysed using a staggering control mode. An analysis of the current ancillary service payments confirms that these are insufficient to ensure widespread uptake by the small consumer, and new mechanisms need to be developed to make becoming an active consumer attractive. Demand response is proposed as a new ancillary service called ramping capability, as the need for this service will increase with more renewable energy penetration on the power system.

## KEYWORDS

Ancillary services; demand response; fridge-freezer; price control strategy; smart grid.

## 1. Introduction

The term ‘smart grid’ has been introduced worldwide to mean the 21st century power system and the associated modernisation of power systems, with the deployment of information and communication technology to previously unmonitored parts of the distribution system, with the aim of using real time measurement to increase its efficiency. The stochastic nature of wind and other renewable generation, which is often out of synchronization with electricity consumption, increases the flexibility and reserve requirements of power systems [1]. The single electricity market (SEM) in Ireland is currently experiencing instantaneous wind penetration of more than 60% [2]. This creates a favourable scenario for the deployment of smart grids including energy storage systems [3] and demand response [4], due to the SEM’s size and scale, ambitious renewable energy targets [5], high levels of wind power and relative isolation, and the fact that it operates in two jurisdictions with different grid codes, policy targets and currencies. The SEM in Northern Ireland and the Republic of Ireland has a unique opportunity to lead the way in smart grid system introduction and development as a European test system. This has been recognised already by the European Union, and a large smart grid project has been allocated for Ireland under the Innovation and Networks Executive Agency as a project of common interest to lower wind curtailment, enhance grid control and establish a cross-border demand side management protocol [6].

Since liberalization, demand response involves the participation of loads in the commercial and industrial sectors [7]. However, residential demand response, which makes up a large proportion of electricity consumption, has not yet been developed in new liberalised markets. It is expected that within the context of a smart grid, consumers will actively participate due to the increased availability of pricing and usage data via smart meter interfaces [8]. The fast growing development in communication technologies is providing the opportunity needed for the consumer to play an important role in the smart grid. Therefore, it should more correctly be called demand side participation, as the consumer has choice in this liberalised environment. Many governments have smart meter targets. The United Kingdom (UK) has a target of installing smart meters in every home by 2020 [9]. Similarly, the Republic of Ireland is piloting a national trial of smart meters which commenced in 2009, with 6,500 consumers using different smart meter technologies [10].

This paper develops an aggregated smart algorithm to control the operation of multiple fridge-freezers within permissible temperature settings of the thermostat. The smart algorithm uses a price control strategy to quantify and value the benefits of demand side participation in the SEM in order to optimise wind power integration. The smart control algorithm is developed in MATLAB © and datasets from the SEM are used to model the test system. When there is high wind penetration on the system, such as in December 2014 when the average wind penetration was 27.1% [2], the day ahead wholesale electricity price fluctuated the most reaching values up to 500 €/MWh [11]. This study shows that demand side participation can play an important role by reducing the fridge-freezer demand during high electricity prices including those caused by inaccuracies in wind forecast and the variability of wind power.

The paper is divided into six sections. The future smart grid and demand response measurements are introduced in Section 1. In Section 2, a review of smart load in the context of smart grid is outlined. Section 3 explains the methodology developed to perform the research, describing the model of a single refrigeration unit followed by the aggregate model, the price control strategy implemented is then explained and the ancillary services in the SEM. Section 4 presents the results and analysis of the implementation of the control strategy on the Irish system demand, current ancillary services in the SEM are analysed to evaluate the ancillary service payments when demand side participation provides this service, and the concept of ramping capability is explored as a new ancillary service needed in high wind penetration systems. Sections 5 and 6 present the discussion and conclusions.

## **2. Smart load in the context of smart grids**

Today's grids are facing many challenges [1] associated with increased renewable power penetration (e.g. system balance, ramping and curtailment). Demand side participation is a scheme that can help to tackle these challenges and provide significant economic and environmental benefits. The participation of domestic loads of individual households can possibly reduce the stress on the local grid [12], creating value for the distribution network operator [4]. It has also been suggested that demand side participation could provide spinning reserve [13]. Schedulable-interruptible loads [14] using an external on/off signal would not significantly affect the consumer experience and performance of a domestic appliance. For example, the system would ensure food safety at all times and it would not apply demand

side participation when the door was open. The objective of demand side participation in the smart grid is to use these schedulable-interruptible loads to reduce peak demand, mitigate system disturbances, delay or avoid additional capital investment in new power plants and prevent excessive use of more expensive or less efficient power plants. Some domestic appliances (e.g. fridge-freezers, tumble dryers and washing machines), electric heating and heat pumps [15] are considered schedulable-interruptible appliances, making them prime candidates to implement demand side participation.

InterTradeIreland is a regional trade and business development agency which gives support to small businesses, with the aim of building networks and partnerships between Northern Ireland and the Republic of Ireland. Its study [16] mentions that small electrical appliances account for a maximum of 20% of the total Irish electrical market and this is currently a growing market. A forecast study has been carried out to assess the predicted consumption by schedulable-interruptible loads in Northern Ireland between 2012 and 2025 [14]. The study showed that the energy consumption of cold appliances is anticipated to be approximately 10% of total domestic consumption by 2025, considering the low total demand forecast case projected by the System Operator for Northern Ireland (SONI) [5].

Electric heating has previously been studied and proposed as a candidate for demand side participation. Fitzgerald et al. [17] showed the power system benefits from implementing direct load control in electric water heating in Ireland. Domestic appliances such as fridge-freezers, chest-freezers and refrigerators are potential candidates because there is at least one of these appliances in every household and they possess thermal storage capabilities. Most researchers to date have focused on refrigerator loads [18-20] and domestic freezers [21], analysing the potential load-shifting effect and time of use tariffs to reduce power peaks. Short et al. [22] presented a study to provide frequency response to the power system using refrigerators. Specifically for fridge-freezers, many studies have focused on different operating factors such as the effect of ambient temperature, door opening and thermostat opening position [23], the use of different types of refrigerants [24] or the effect of different types in components of the refrigeration cycle [25]. The potential response from relevant responsive loads such as refrigeration and space heating has been analysed in a statistical manner [1]. The results indicate that the residential sector deserves attention as a potentially valuable demand side participation resource.

### 3. Methodology

In this research a fridge-freezer with only one compressor is modelled because it is the most widely sold domestic appliance in the UK [26] and in countries with similar climates to Ireland. The thermodynamic cycle in the cooling circuit is a vapour compression cycle [27]. In this appliance the circulation of the refrigerant is driven by a compressor, which requires a motor and thus electrical energy.

#### 3.1. Model of a single fridge-freezer

The model of a single fridge-freezer developed in [28] predicts the temperature in each compartment of the fridge-freezer based on heat transfer equations [27]. The model used in this study is a simplified model in which it is not necessary to know the detailed technical specifications of each component of the refrigeration cycle to obtain an accurate prediction of the temperature in each compartment and therefore an accurate prediction of the electrical power consumption. The model inputs are the dimensions of the fridge and freezer compartments, the compressor power consumption, coefficient of performance (COP) tested in extreme working conditions, thermal masses and thermal time constants of the fridge and freezer.

The heat transfer equation for each compartment of the fridge-freezer is (1), which states that the heat transmitted to the thermal mass of the fridge-freezer compartment is equal to the convection heat losses, resulting from the temperature difference between the room and the compartment, minus the heat transfer from the refrigerant to the compartment. The conduction heat losses between the fridge and freezer are assumed to be negligible due to the insulation.

$$-(m_w c_{p_w} + m_a c_{p_a}) \frac{dT(t)}{dt} = \frac{(T_{room}(t) - T(t))}{R_{eq}} - Q \quad (1)$$

where  $m_w$  (kg) and  $m_a$  (kg) are the mass of the water and air stored in each compartment,  $c_{p_w}$  (J/kg°C) and  $c_{p_a}$  (J/kg°C) are the specific heat of water and air,  $T_{room}$  (°C) is the room temperature,  $R_{eq}$  (W/°C) is the overall heat transfer coefficient,  $Q$  (W) is the heat transferred

from the refrigerant to the compartment, and  $T(t)$  ( $^{\circ}\text{C}$ ) is the temperature in the compartments.

The overall heat transfer coefficient is calculated from the thermal time constant ( $\tau$ ) using (2). The thermal time constant of the freezer compartment is referred to as ‘temperature rise time’ in the manufacturer technical specifications.

$$R_{eq} = \frac{(m_w c_{pw} + m_a c_{pa})}{\tau} \quad (2)$$

The variation of the room temperature throughout the day is simulated using a sinusoidal waveform (3).

$$T_{room}(t) = T_{room,mean} + 2 \sin\left(\frac{2\pi}{86400}t - 0.85\pi\right) \quad (3)$$

where  $T_{room,mean}$  is the mean temperature during the day.  $T_{room,mean}$  is assumed to be  $16^{\circ}\text{C}$  during winter and  $22^{\circ}\text{C}$  during summer. In both cases the maximum temperature during the day occurs in the afternoon and a variation of  $4^{\circ}\text{C}$  in the room is assumed. Typically a fridge-freezer is located in a household kitchen, which is generally a heated and relatively confined space.

The power consumption of the compressor is modelled according to (4) [21], which includes a starting transient.

$$\left. \begin{aligned} W_c &= 0 \text{ if } t < t_0 \\ W_c &= 16e^{\frac{-(t-t_0)}{10}} + W_{c,spec} \text{ if } t \geq t_0 \end{aligned} \right\} \quad (4)$$

where  $t_0$  is the time in the cycle at which the compressor is switched on and  $W_{c,spec}$  is the specified compressor power.

The coefficient of performance varies according to (5), which relates the working conditions to the specified COP ( $COP_{spec}$ ) and the theoretical COP ( $COP_{theoretical}$ ) according to Carnot’s law.

$$\text{COP} = \left( \frac{\text{COP}_{\text{spec}}}{\text{COP}_{\text{theoretical}}} \right) \cdot \left( \frac{T_c}{T_h - T_c} \right) \quad (5)$$

198

199 where  $T_c$  corresponds to the temperature in the cold reservoir, in this case the freezer  
 200 temperature, and  $T_h$  corresponds to the temperature in the hot reservoir, in this case room  
 201 temperature.

202

203 The total heat transferred ( $Q$ ) from the refrigerant to both compartments is obtained by  
 204 relating the COP to the compressor power consumption ( $W_c$ ) (6). The proportion of the heat  
 205 transferred to each individual compartment is calculated taking into account the measured  
 206 room and compartment temperatures.

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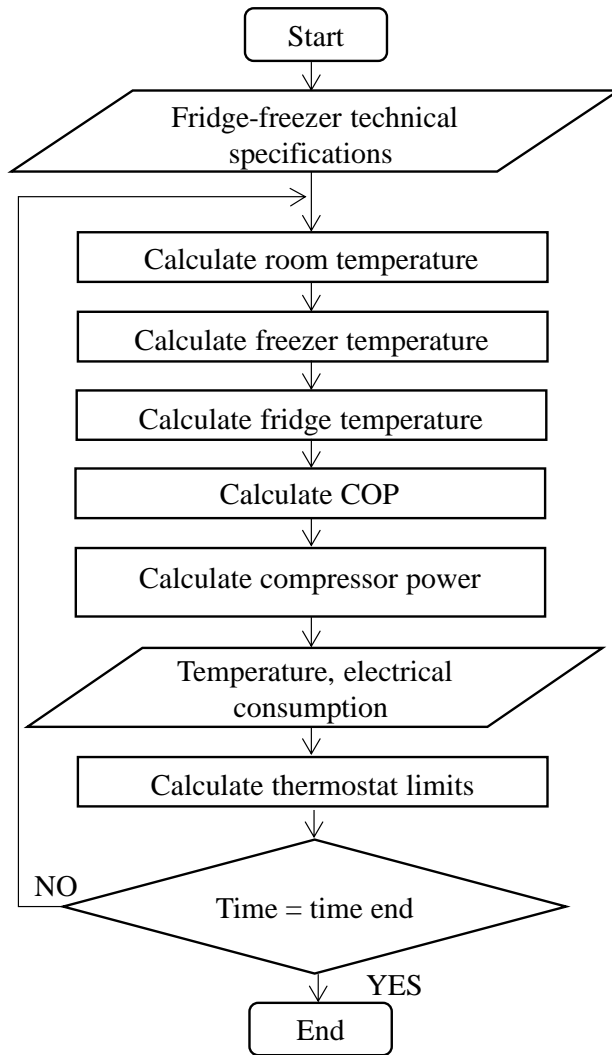
$$Q = \text{COP} \cdot W_c \quad (6)$$

209

210 The flowchart to model a single compressor fridge-freezer is shown in Fig.1. The flowchart  
 211 shows every step of the model which is run for a given time. The inputs to the model are  
 212 initialized using the fridge-freezer technical specifications. The temperature of the room is  
 213 calculated according to (3). The temperature in each compartment of the fridge-freezer is  
 214 calculated by solving (1) in each subroutine. With both temperatures obtained the COP is  
 215 calculated by solving (5). The power of the compressor is calculated using (4) and the  
 216 temperatures and electrical consumption values are saved for further analysis. The thermostat  
 217 limits vary depending on the control strategy being applied.

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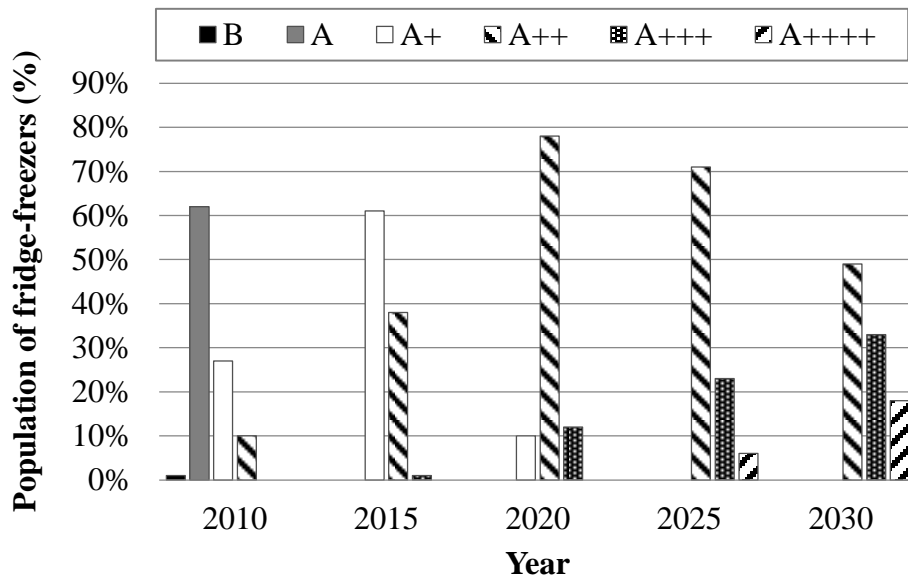
**Fig. 1.** Flowchart of the single compressor fridge-freezer.

### 3.2. Aggregate model

The study uses a model to simulate each device and aggregates their individual behaviour to predict the demand of the aggregate load. The aggregate fridge-freezer model simulates a thousand units, the simulations have been performed considering different features of each unit depending on the scenario under study. The time span for cooling is not a fixed parameter [18-20], as it depends on the characteristics of the appliance and the thermal mass inside each cabin. Randomness following a standard uniform distribution has been added to the model with the objective of creating a more realistic solution, specifically to the temperature limits  $\pm 0.5^{\circ}\text{C}$ , the overall heat transfer coefficient  $\pm 0.01\text{W}/^{\circ}\text{C}$  and thermal mass that varies randomly between 17% to 31% of water equivalent volume inside each compartment. The results obtained are extrapolated to the forecast total population of fridge-freezers to evaluate the impact of using this smart appliance application in Ireland. The total

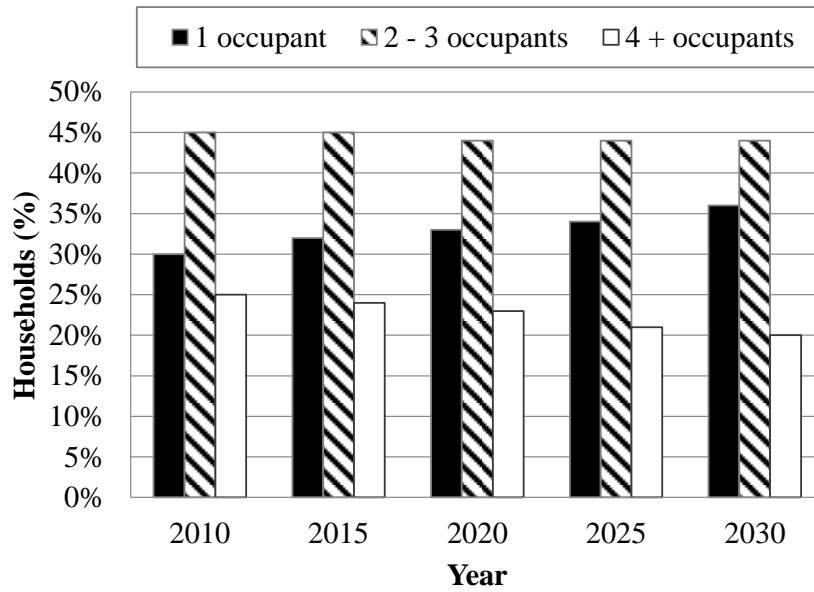
population of fridge-freezers is estimated to be 2,700 thousands by 2020 calculated from [29-30].

In coming years people will buy more efficient appliances as prices come down, but in 2025 there will remain a significant number of fridge-freezers sold in the 2010's due to the life of these appliances. The expected percentages of fridge-freezers in the UK projected to fall in each energy label class until 2030 are shown in Fig. 2 [31].



**Fig. 2.** Expected percentage of fridge-freezers in the UK depending on the energy label class [31].

Fig. 2 indicates that by 2020 approximately 80% of fridge-freezers are expected to be A++ rated. The year to study selected is 2020 as the simulation inputs can be simplified. In the current study variation of device size is included but all are considered to be of the dominant energy rating. The Northern Ireland Statistics and Research Agency (NISRA) [29] has forecast the number of households by the number of occupants. This study assumes that the forecast for Northern Ireland applies also to the Republic of Ireland, for which no data are available. Fig. 3 shows the expected distribution of the number of occupants per households in Ireland.



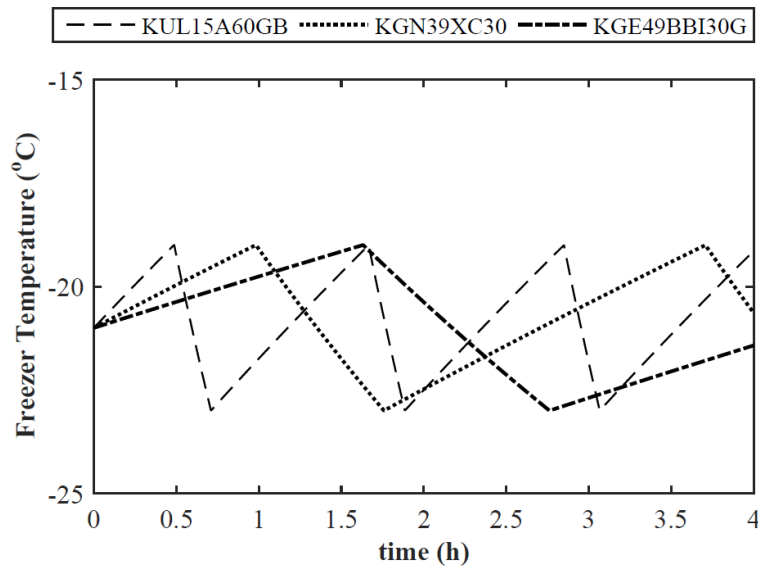
**Fig. 3.** Expected percentage of households in Ireland depending on the number of occupants.

It is assumed that households with one occupant have a small fridge-freezer, households with two or three people have a medium size fridge-freezer and that households with four or more people will have a large size fridge-freezer. The technical specifications of a fridge-freezer are summarized in Table 1, together with the overall heat transfer coefficient ( $R_{eq}$ ). The overall heat transfer coefficient for the freezer compartment is given by the manufacturer and for the fridge compartment is obtained by running the model for one unit with the data provided by the manufacturer, allowing for a 5% error in the energy consumption.

**Table 1.** Technical specification of A++ fridge-freezers of different size [32].

Size	Small	Medium	Large
<b>Model</b>	KUL15A60GB	KGV33VL31G	KGE49BBI30G
<b>Energy class</b>	A++	A++	A++
<b>Energy consumption (kWh/annum)</b>	140	219	255
<b>Storage vol. fridge (l)</b>	108	192	301
<b>Storage vol. freezer (l)</b>	15	94	111
<b>Temp. rise time (h)</b>	10	23	44
<b>COP</b>	1.02	1.3	1.05
<b>Comp. power (W)</b>	75	80	90
<b>R<sub>eq</sub> fridge (W/°C )</b>	1	1.3	1.4
<b>R<sub>eq</sub> freezer (W/°C )</b>	0.28	0.87	0.62

Fig. 4 shows the simulated freezer temperatures during four hours of the day for each fridge-freezer model using the technical specifications given in Table 1. The compressor is shown to run more often when the device is smaller due to the lower temperature rise time and COP of the smaller device.



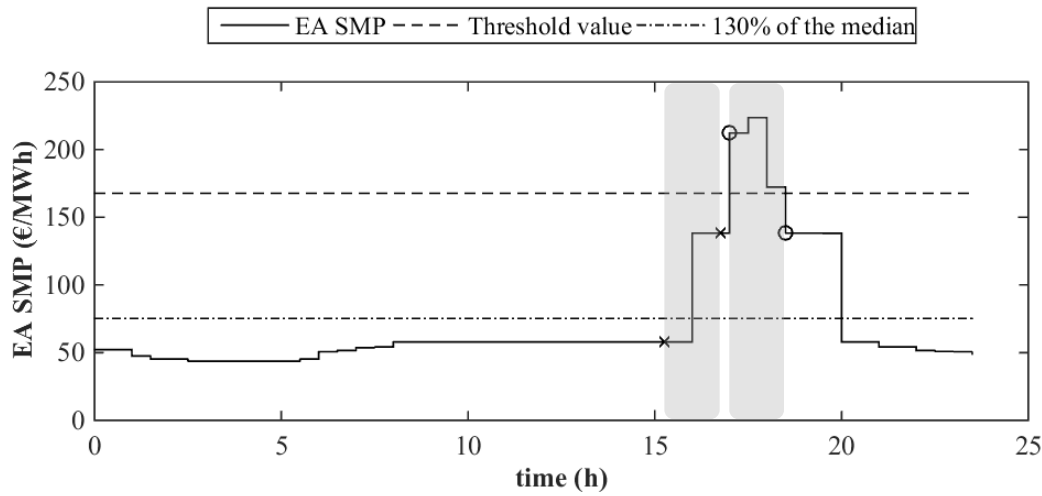
**Fig. 4.** Simulated freezer temperature for each model of fridge-freezer.

### 3.3. Price control strategy

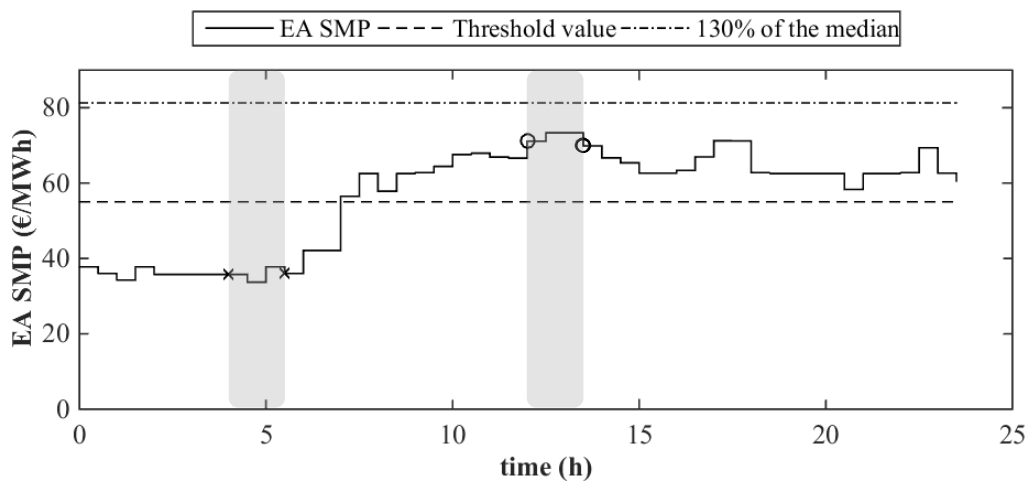
A price control strategy is proposed in this study. The control algorithm is designed to simulate a standard fridge-freezer thermostat, which maintains the freezer temperature between  $-23^{\circ}\text{C}$  and  $-19^{\circ}\text{C}$  and the fridge temperature around  $5^{\circ}\text{C}$ . At chosen periods the thermostat upper and lower temperature limits are varied according to the Ex Ante 1 (EA) system marginal price (SMP). The EA SMP is issued by the Single Electricity Market Operator in Ireland (SEMO) daily and it is calculated one day ahead using forecast data for the trading day [11]. Demand side participation in this study is designed to increase consumption during overcooling periods in order to reduce consumption during peak periods while maintaining food safety. Food safety is considered throughout the model, the restrictions of  $T_{\text{freezer}} < -18^{\circ}\text{C}$  and  $3^{\circ}\text{C} < T_{\text{fridge}} < 7^{\circ}\text{C}$  are applied in the freezer and fridge compartments respectively. The temperature rise time is highly dependent on the amount of food present in the freezer. This is primarily due to the significant heat transfer resistance in the food inside the compartment. Therefore the average temperature in each compartment of the fridge-freezer (combined air and water) has been modelled using the temperature rise time data provided by the device manufacturer, allowing for a 5% error in the energy consumption (kWh/annum).

The length of the peak price period depends on the shape of the peak and its maximum is considered as 1.5 hours to avoid any possible mechanical damage for running the compressor more than necessary. Fig. 5a and b show the SMP on a typical winter/summer day. The threshold value chosen is 75% of the maximum EA SMP price. The algorithm of the control strategy analyses the shape of the peak, the peak price period starts one hour before the EA SMP peak if this EA SMP is greater than the threshold and the EA SMP after the peak. The peak period is the period between the symbols ‘o’ in Fig. 5. In first evaluations prior to this study an overcooling period of 1.5 hours has been found that produces the desired effect of modifying system demand while not giving rise to significant disturbances caused by the devices returning to the standard limits. The end of the overcooling period is defined as 15 minutes before the peak period starts. The overcooling period is the period between the symbols ‘x’ in Fig. 5. However, when the EA SMP remains flat during the day, i.e. the EA SMP peak is less than 130% of the median of the EA SMP during the day, the overcooling

period occurs at the same time as the price valley period. The overcooling period starts 30 minutes before the minimum EA SMP occurs: see Fig. 5b.



a



b

**Fig. 5.** SMP on a typical winter/summer day.

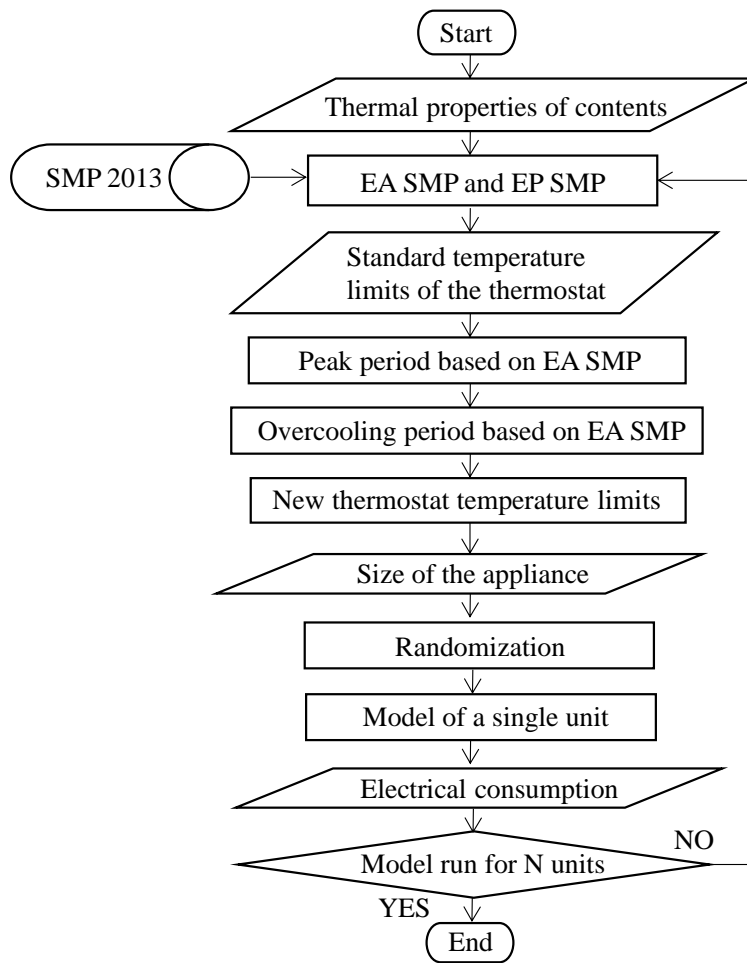
**a** Overcooling and peak periods on a typical winter day (9th December 2013).

**b** Overcooling and peak periods on a typical summer day (24th July 2013).

During the overcooling period the thermostat temperature limits are modified to maintain a freezer temperature between  $-25^{\circ}\text{C}$  and  $-23^{\circ}\text{C}$ , while to prevent freezing the fridge temperature is maintained above  $3^{\circ}\text{C}$ . During the peak period the limits are modified to maintain the freezer temperature between  $-18.5^{\circ}\text{C}$  and  $-18^{\circ}\text{C}$  and the fridge temperature under  $7^{\circ}\text{C}$ . The lower bound of  $-18.5^{\circ}\text{C}$  has been introduced with the aim of controlling and reducing the consumption of the fridge-freezer during the peak period. Load shift could

introduce an undesired effect such as creating an unexpected peak. By maintaining a small bound in the thermostat, the compressor would be running for a very short, time keeping the consumption flat and avoiding peaks during the peak period. The aim of this control strategy is to avoid electricity consumption at high SMP periods.

Fig. 6 shows the flowchart of the aggregate model using the price-based control strategy. The flowchart shows every step of the aggregate model which is run for a number of units. The model starts by initializing the inputs to the model. The model is run for a given time. EA SMP and the Ex Post Indicative (EP) SMP are obtained from the SMP 2013 data available. EP SMP is issued one day after the trading date. The standard temperature limits of the thermostat are set up, which are modified in the following subroutine based on the calculated peak price and overcooling periods using the EA SMP. Subsequently the size of the appliance is selected according to the expected percentage given in Fig. 3. Randomization according to a standard uniform distribution is applied to the temperature limits, overall heat transfer coefficient and thermal mass. A single unit is modelled and the electrical consumption of that device is saved for analysis. The process ends when the model runs for the number of units specified.



**Fig.6.** Flowchart of the aggregate model using price control strategy.

### 3.4. Ancillary services

Ancillary services in the power system are the services which maintain the power quality, security and reliability of the system. There is increasing interest in the utilization of demand side participation to address the integration of wind generation. Demand side participation can provide ancillary services to aid supply/load balance and also augment morning and evening ramping requirements [38].

Currently ancillary services in the SEM [34] are frequency regulation, reserve, reactive power support and black start capability. Analysing the current options of ancillary services, the ensemble of fridge-freezers could be considered as interruptible load, or short term active response (STAR), making the load available to the System Operator for short-term interruptions. Also it could provide Tertiary Operating Reserve 1 (TOR1) where the response times are 90 seconds to 5 minutes. TOR1 is provided in the SEM by thermal generation, but this paper proposes that the domestic appliances could provide part of this ancillary service.



The domestic appliances will respond to a signal from the system within 90 seconds and remain activated for at least 5 minutes, with the opportunity to be activated for a maximum of 1.5 hours during the overcooling and peak periods if required.

In the SEM the minimum demand side participation demand reduction capacity is 4 MW in the regulating power market [7]. In the electricity wholesale electricity market in Great Britain (BETTA) the minimum bid capacity is 3 MW as STOR [35]. Currently the SEM spends around 60 M€/year on ancillary services [36], i.e. 164,000 €/day. The operating reserve payments are calculated according to (7):

$$\text{Payment} = \text{Available SOR} \cdot \text{SOR Rate} \cdot \text{Trading Period} \quad (7)$$

where Available SOR (system operating reserve) is the available system operating reserve, and the trading period is considered to be 24 h/day.

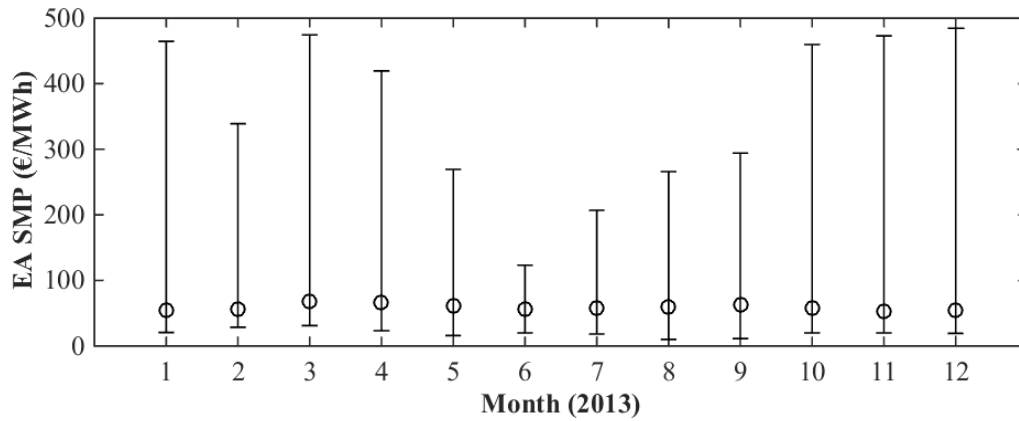
A recent study published by the System Operator in Ireland [37] suggested that there is a need for new ancillary services. An increase of ancillary service payments could reduce the overall system cost through preventing wind curtailment [38]. A new service called ramping margin is under study. Ramping margin tries to manage the uncertainty and variability in a system with high levels of wind penetration. Ramping margin is defined as an increase or decrease in MW demand that can be delivered with a good degree of certainty by a thermal generator or demand side participation during a time horizon and sustained for a period. Demand side participation could play an important role when the ramping capability of the thermal generation is not adequate. It is necessary to evaluate the ramping capability needed to accommodate wind generation, as the ideal situation is that the demand is balanced by the wind generation to avoid using expensive power plants.

## **4. Results and analysis**

### **4.1. Selection of the time period for analysis**

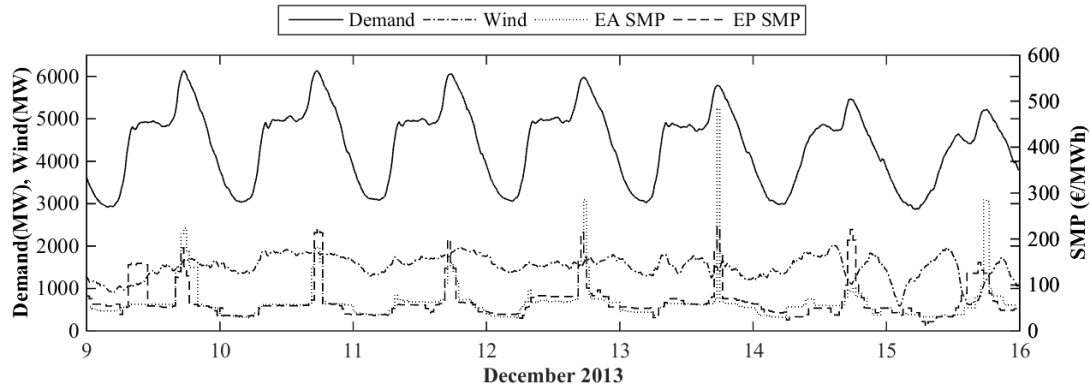
The model is run for one typical week in winter and one typical week in summer to evaluate the effect of the proposed control strategy on the Irish system demand. These periods have been identified, after the analysis of the SMP during the whole year, because they contain contrasting patterns of more extreme variations in price, system demand and wind generation.

Fig. 7 shows the analysis of the EA SMP where the maximum, minimum and median value of the EA SMP have been calculated every month of the year 2013. The month of December shows the greatest variation between maximum and minimum EA SMP, while the minimum variation between maximum and minimum EA SMP occurs in June. However, this particular month is not chosen for analysis as on most days the price remains flat. Therefore, the month of July is chosen for analysis.

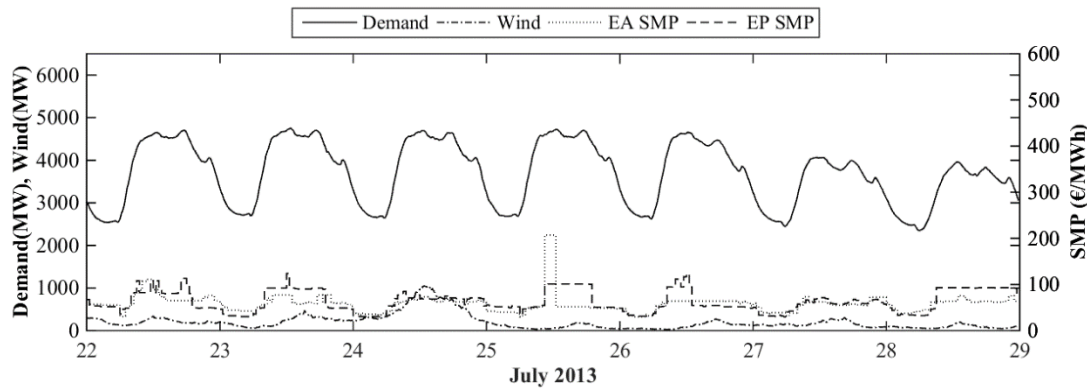


**Fig.7.** Analysis of the SMP during the year 2013.

Fig. 8a shows the SEM system demand and wind generation for the winter week from the 9th – 15th December 2013 [39], in which the average wind penetration is 35.4%. Fig. 8b shows the values on the summer week from the 22nd – 28th July 2013 [39], in which the average wind penetration is 5.3%. Both figures show the EA SMP and EP SMP. During the winter week the peak system demand is very clear, occurring around 17:30, thus the maximum EA SMP and EP SMP occur around this time. However, during the summer week the peak system demand is not as obvious as during winter. For this reason the maximum EA SMP and EP SMP may occur at different times and possibly not coincide with peak system demand. An EA SMP price value of more than 500 €/MWh is observed in Fig. 8a. Such an increase in price could be caused by inaccuracies in wind forecast error and wind variability, leading to a reduced EP SMP price at the time of peak demand.



a



b

**Fig. 8.** System demand, wind generation, EA and EP SMP in 2013 in Ireland.

**a** Winter week (9th – 15th December 2013).

**b** Summer week (22nd – 28th July 2013).

In 2020 the system demand is assumed to be 10% greater than the equivalent day in 2013. According to EirGrid the demand is forecast to grow 2% each year [5] after the recovery of the economy in 2015. For this study SMP prices are assumed to remain the same. Fridge-freezers are assumed to be A++, i.e. moderately efficient, and have the size range estimated from [33].

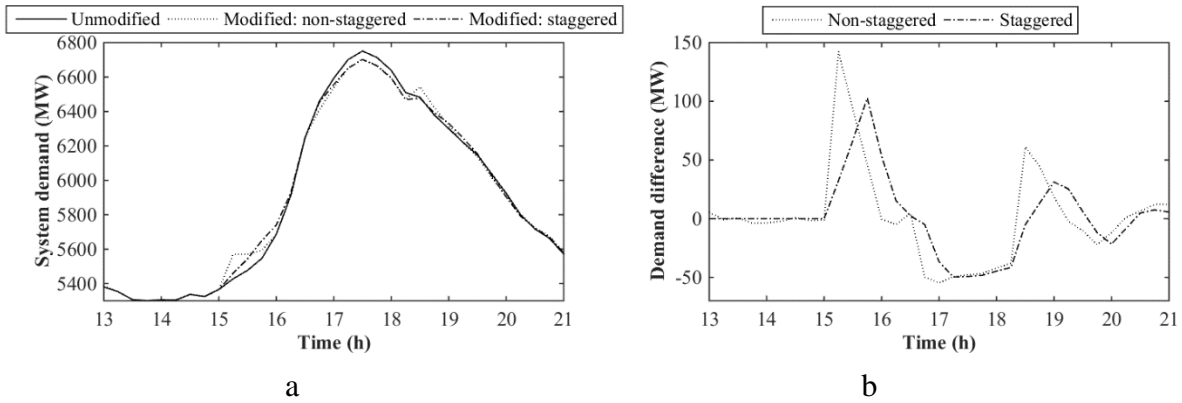
#### 4.2. Application of the price control strategy

Two different modes of control have been studied for the winter week:

- Non-staggered. All the devices are given the same overcooling and peak period starting times in which to operate the control strategy. All the devices are in different stages of the cooling cycle when the overcooling and peak periods are initiated.

- Staggered. The starting time of the overcooling and peak periods for individual devices within the aggregate are distributed over a period of 30 minutes. Every minute the control strategy of a proportional number of devices is modified, i.e. for the simulation of 1000 units, 34 units are chosen to be activated every minute.

Fig. 9a shows the effect of the non-staggered and staggered control modes on the system demand for the first day of the winter week analysed. Fig. 9b shows the demand difference due to the application of each control mode.



**Fig. 9.** Proposed modified system demand in Ireland on the first day of a winter week.

**a** Unmodified, non-staggered and staggered modified system demand.

**b** Demand difference due to the application of the control strategy.

Subsequently the fridge-freezer operating costs are calculated and day ahead and real cost are compared. Day ahead cost (EA cost) and real cost (EP cost) are calculated using EA SMP and EP SMP respectively. For the non-staggered control mode the fridge-freezer operating EP cost is decreased by 8.9% compared to the fridge-freezer operating EP cost using no control strategy, as shown in Table 2. However, it was expected to decrease the operating cost by 11.8%, based on EA SMP. The percentages have been calculated using the EP cost for unmodified demand as a reference value. As shown in Fig. 8a the maximum EP SMP does not always occur at the same time as EA SMP. For the staggered control mode the fridge-freezer operating EP cost is decreased by 7.6% compared to the expected reduction of 12.5%. The aim of this control strategy is to avoid high SMP periods, defined in this study as peak periods. During the peak period for the non-staggered control mode the EP cost is decreased by 76.4% and for the staggered control mode the EP cost is decreased by 80.6%, because the load is shifted to other parts of the day. It is worth noting that load shifting in this

manner resulted in an increase of 1% of the energy consumed during the whole week in the non-staggered and staggered control modes.

**Table 2.** EA and EP fridge-freezer operating cost and the percentage of change in fridge-freezers operating cost during the winter and summer week.

Week	Control mode	EA cost		EP cost	
		(€)	(%)	(€)	(%)
<b>Winter</b>	Unmodified	-		595,172	
	Non-staggered	525,202	-11.8	541,958	-8.9
	Staggered	527,617	-12.5	550,039	-7.6
<b>Peak period (winter)</b>	Unmodified	-		97,074	
	Non-staggered	26,747	-72.4	22,923	-76.4
	Staggered	20,261	-79.1	18,839	-80.6
<b>Summer</b>	Unmodified	-		595,310	
	Modified a	535,502	-10	591,906	-0.6
	Modified a staggered	532,484	-10.6	593,008	-0.4
	Modified b	543,210	-8.8	590,716	-0.8
<b>Peak period (summer)</b>	Unmodified	-		50,563	
	Modified a	28,181	-44.3	27,280	-46
	Modified a staggered	18,152	-64.1	17,465	-65.5
	Modified b	44,838	-11.3	40,077	-20.7

High SMP periods might not occur at the same time as the peak system demand. The non-staggered control mode creates a second peak, as shown in Fig. 9, when the devices revert to the standard thermostat settings. For the non-staggered control mode the maximum system demand in the peak period is decreased on some days but increased on others. The increase is undesirable; the demand can be modified by -53 MW to +5 MW. However, the staggered mode results in a more consistent peak reduction between -54 MW to -40 MW.

The analysis in detail of the first day of the winter week presented in Fig. 9b shows that the power peak that occurs during the overcooling period in the staggered control mode is 40

MW smaller than in the non-staggered control mode, as shown in Table 3. Fig. 9b also shows how during the peak period the consumption is reduced by 55 MW and 50 MW in the non-staggered and staggered modes respectively. The effect of staggering the devices offers a smoother fluctuation in the demand compared to the non-staggered control mode, a reduction of 30 MW.

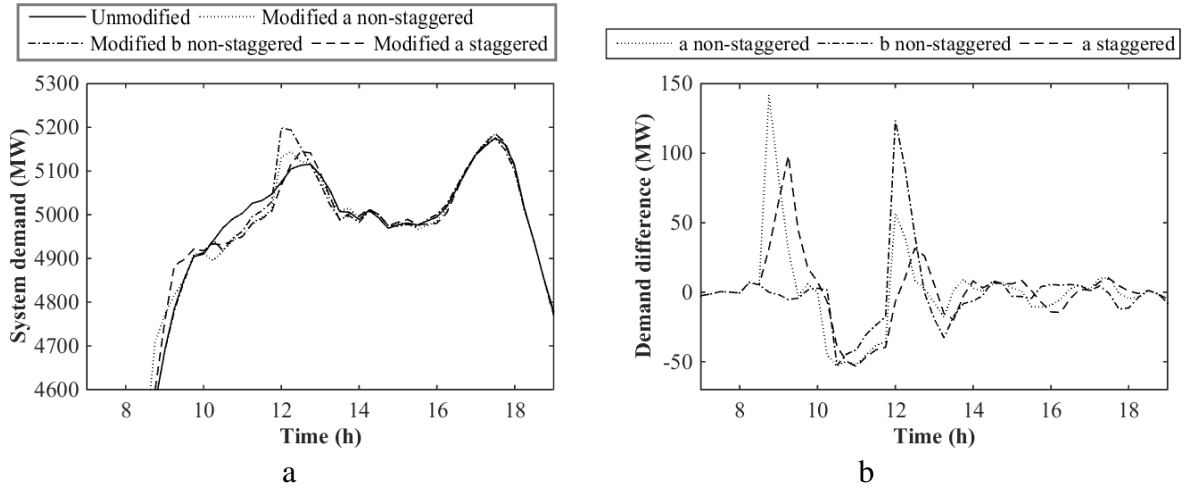
**Table 3.** Modified demand for the proposed control modes in the first day of the week.

Period	Control mode	Modified demand (MW)		Peak return standard limits (MW)
		Overcooling period	Peak period	
<b>Winter</b>	Non-staggered	+ 143	- 55	+ 61
	Staggered	+ 103	- 50	+ 31
<b>Summer</b>	a non-staggered	+ 142	- 53	+ 57
	a staggered	+ 98	- 53	+ 31
	b non-staggered	+ 7	- 53	+ 124

Two different modes of control have been studied for the summer week:

- Control mode ‘a’. All the devices are given the same overcooling and peak period starting times in which to operate the control strategy. All the devices are in different stages of the cooling cycle when the overcooling and peak periods are initiated.
- Control mode ‘b’. During the overcooling period the temperature limits of the thermostat remain as the standard temperature limits (-23°C to -19°C). All the devices are given the same peak period starting time in which to operate the control strategy. This control mode has been suggested because the variation of the SMP might not be significant during summer, meaning that overcooling the device during the overcooling period may not be appropriate.

Fig. 10a shows the effect of the non-staggered control mode ‘a’ and ‘b’ on the system demand. Fig. 10b shows the demand difference due to the application of each control mode.



**Fig. 10.** Proposed modified system demand in Ireland on the first day of a summer week.

**a** Unmodified, control mode ‘a’ and ‘b’ non-staggered and control mode ‘a’ staggered modified system demand.

**b** Demand difference due to the application of the control strategy.

For the non-staggered control mode ‘a’ the fridge-freezer operating EP cost is decreased by 0.6% as shown in Table 2. However, it was expected to decrease by 10%. As shown in Fig. 8b, the patterns of EP SMP and EA SMP may differ significantly. For control mode ‘b’ the fridge-freezer operating EP cost is decreased by 0.8%. For the staggered control mode ‘a’ the EP cost is decreased by 0.4%. During the peak period for the non-staggered control mode ‘a’ the EP cost is decreased by 46%, while for control mode ‘b’ the EP cost is decreased by 20.7%. For the staggered control mode the EP cost is decreased by 65.5%. The load is shifted from the peak period to other parts of the day, incurring an increase of 0.3% in the energy consumed during the whole week in the case of control mode ‘a’ and in the case of control mode ‘b’ in a reduction of 0.5% of the energy consumed. The latter is a result of the device not being overcooled when not appropriate according to the control strategy definition, hence the average temperature in the fridge-freezer is greater compared to the standard working condition, leading to reduced consumption.

The non-staggered control mode creates a second peak, as shown in Fig. 10, when the devices revert to the standard thermostat settings. For the non-staggered control mode the maximum system demand in the peak period is decreased on some days and increased on others. The demand can be modified by -23 MW to +57.1 MW. The staggered mode results in a peak

modification between -31 MW to +54.1 MW. The increase in the peak of 57.1 MW occurs on the fifth day of the week because on that day the maximum EA SMP occurs much earlier than the EP SMP price, which occurs at the same time as the peak system demand and which coincides with the peak system demand as shown in Fig. 8b. Thus the implementation of the price signal control strategy could mean undesirable peaks during the summer, which would only be desirable if these occur at the same time as a wind generation peak.

The analysis in detail of the first day of the summer week presented in Fig. 10b shows that the power peak that occurs during the overcooling period in the non-staggered control mode 'a' is 135 MW greater than in the control mode 'b', as shown in Table 3. The staggered and non-staggered control mode 'a' comparison offers a reduction of 44 MW during the overcooling period. Fig. 10b also shows how during the peak period the consumption is reduced by 53 MW. The effect of non-staggering the devices in which the return to the standard limits of the thermostats offers a greater fluctuation in the demand comparing 'a' and 'b', an increase of 67 MW. The staggered and non-staggered control mode 'a' comparison offers a reduction of 26 MW during the return to the standard limits of the thermostat.

#### 4.3. Ancillary services evaluation

Participants receive a capacity payment when they provide an ancillary service. For the SEM in the period 2014-2015 the SOR rates are shown in table 4. The average load of the aggregate fridge-freezer calculated is 58.42 MW. Assuming the ancillary payment rates remain the same as for the period 2014-2015, and if each fridge-freezer in Ireland provides TOR1 and STAR in 2020, the ancillary payment will be 14,077 €/day, i.e. 2,580 €/day due to TOR1 and 11,497 €/day due to STAR. This represents 8.4% of the total amount that the SEM spends on ancillary services.

**Table 4.** Ancillary services aggregated fridge-freezer forecast payments.

Type	Available SOR (MW)	SOR Rate (€/MWh)	Trading Period (h/day)	Ancillary service payment (€/day)
Tertiary Operating	58.42	1.84	24	2,580

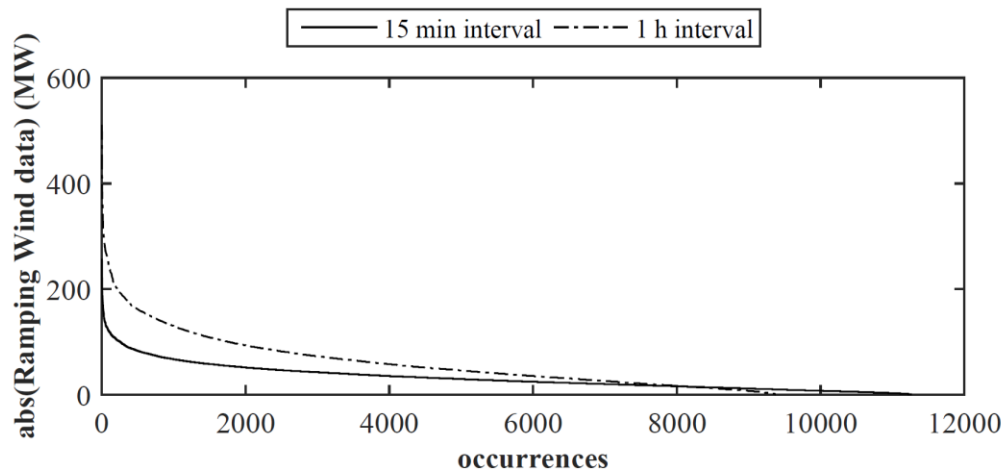


<b>Reserve (TOR1)</b>				
<b>Short term active response (STAR)</b>	58.42	8.20	24	11,497

Assuming each consumer receives the payment for providing ancillary services TOR1 and STAR, the reward would be 1.90 €/year.

#### 4.4. Ramping capability as a new ancillary service

A pattern is observed by analysing the ramping rates from wind generation data published by the System Operator in Ireland in 2013 [33], for 15 minute and 1 hour time horizons, as shown in Fig. 11. The pattern indicates that the ramping capability needed in 15 minutes is typically half of the ramping needed in 1 hour.



**Fig. 11.** Ramping rate in wind generation data in 2013.

Fig. 9 and Fig. 10 show that a price signal control strategy could modify the Irish system demand. The ramping rate in wind generation data shows that the highest ramping rates occur during December, which had a monthly average wind penetration of 28.4%, compared to July, which had a monthly average wind penetration of 6.6%. This study focuses on analysing the ramping capability during the winter week as the wind penetration is greater. For the non-staggered control mode the increase of the temperature limits of the thermostat during the peak period in the first day of the week results in a reduction of the 15-minute ramping capacity from 213 MW to 159 MW due to the system demand peak reduction. For the staggered control mode the 15-minute ramping capacity is reduced from 134 MW to 102

MW, avoiding the use of power plants with high ramping rates as they tend to be more polluting and expensive to run. The temperature limits of the thermostat can also be reduced, allowing more wind on the system that might otherwise be curtailed. The results clearly show that the aggregation of fridge-freezers in Ireland has useful ramping potential.

## **5. Discussion**

The potential to modify the system demand by applying a price control strategy using the energy storage of a fridge-freezer and its impact on cost savings have been quantified for the SEM power system in Ireland. During the winter week peak demand modifications of -54 MW to +5 MW are achieved. A peak demand reduction of at least 40 MW is achieved when using a staggered control mode, assuring a peak reduction of at least 68% of the average winter refrigeration load. During the summer week demand modifications of -31 MW to +57.1 MW are achieved. Here it is more difficult to predict the modification, as the peak of the EA SMP may not occur at the same time as the peak demand. Overall refrigeration running costs could be reduced on average by 8.2% during a typical winter week and by 0.6% during a typical summer week. The study also shows an increase in appliance energy consumption of 1% during the winter week, an increase of 0.3% during the summer week using control mode 'a' and a reduction of 0.5% of the energy consumed using control mode 'b' during the summer week, as the latter mode does not overcool the appliance during the valley periods.

The current residential tariffs offered by electricity retailers are a barrier for residential customers to provide demand side participation. Maximum benefit from demand side participation will come from dynamic tariffs, because if the price varies over only a small range, the savings for consumers may not be sufficient to encourage demand side participation schemes. During the winter week EA SMP and EP SMP follow the same distribution, thus the day ahead market provides a reasonable solution. However, during the summer the prices are flatter and EA SMP may differ substantially from EP SMP, thus there are some days when it might be better not to apply the control strategy because there is insufficient reward. This is largely due to the fact that the SMP peak is greater in the winter than in the summer. In the winter week peak shavings are more predictable as the EP SMP peak occurs very close to the EA SMP peak. However, in the summer peak demand can be

increased by +50 MW which is clearly only desirable if peak demand occurs at the same time as a generation surplus, such as an increase in wind generation.

The reward that each consumer receives as payment for providing the ancillary services TOR1 and STAR is calculated as 1.90 €/year. Clearly this reward seems insignificant, and some modification to the reward mechanism will be required if individual consumers are to be encouraged to play an important role as an aggregate consumer. It is anticipated that to attract significant buy-in, a payment of at least 25 €/year would be required, meaning that the current ancillary TOR1 and STAR payment rates would have to be 11 times the current rates. The dramatic increase is not expected in the near future, thus day ahead pricing could be the next step. The utility regulator in Ireland is currently working on a public consultation on demand side participation for the SEM applying day ahead price for industrial and commercial sectors only [10]. Hence TOR1 and STAR may be not be suitable for individual fridge-freezers to provide ancillary services, and perhaps some other mechanism entirely is required.

The clearest benefit of a demand side participation is that winter peak demand can be reduced, especially with the staggered control mode. Application of the demand side participation scheme would reduce the required generation capacity. The result shows that less ramping capacity is required in 15-minute intervals during the winter week if the control strategy is implemented. Demand side participation has the additional benefit, compared to extra generation, of avoided network reinforcement. It is important that consumers offering demand side participation should benefit from a related capacity payment.

This study has shown that aggregated domestic fridge-freezer demand is small compared to the total system demand, therefore the effect is likely to be small. However, this effect could be beneficial under certain circumstances, such as reducing the winter peak demand or reducing wind curtailment. It is proposed that future work will examine the opportunity for domestic fridge-freezer demand side participation in the SEM focusing on Northern Ireland using a unit commitment model to analyse wind curtailment and ramping, effects of grid constraints and ancillary services.

## **6. Conclusions**

This paper presents the results of an aggregated fridge-freezer price control strategy to quantify and value demand side participation savings in Ireland in 2020. A projected range of appliance sizes, allied to random variations in parameters, was used to simulate a population of devices.

The potential to reduce the cost of the system demand using the energy storage of a fridge-freezer has been quantified for a power system, i.e. the single electricity market in Ireland. A price control strategy has been developed based on the day ahead wholesale electricity price. The analysis shows that overall refrigeration running costs could be reduced on average by 8.2% during a typical winter week and significantly lower during a typical summer week. The application of the control strategy caused the overall energy consumed by the devices to increase by 1% during the winter week and by 0.3% during the summer week. Optimization based on cost using storage will increase energy usage, as shown in the study. The proposed scheme should ensure that the cost benefits, CO<sub>2</sub> emissions reduction and enhance system security. The scope for peak reduction is greatest in the winter week, when the peak is well-defined. A peak reduction of at least 68% of the average winter refrigeration load is achieved consistently during the week analysed using a staggered control mode. While the generation capacity saving may be captured implicitly by peak wholesale prices, the network capacity saving is not. Thus it can be argued that consumers offering peak load reduction should qualify for additional rewards related to deferred network investment.

The scope for using domestic refrigeration to provide reserve is also examined. It has been found that the current single electricity market payments are unlikely to justify provision of these ancillary services by the domestic sector. However, there may be scope for using refrigeration load as regulating reserve to provide ramping capability, especially as the demand for this service increases with growing renewable energy penetration.

In conclusion, demand side participation can potentially reduce fossil fuel dependency by optimizing the combination of renewable energy resources and smart controls available to the self-informed customer. Future work will examine the opportunity for demand side participation in the SEM focusing on Northern Ireland using a unit commitment model.

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